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CHARACTERISTICS OF TRAP-FILLED GALLIUM ARSENIDE PHOTOCONDUCTIVE SWITCHES USED IN HIGH GAIN PULSED POWER APPLICATIONS

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INTRODUCTION

The electrical properties of semi-insulating (SI) Gallium Arsenide (GaAs) have been investigated for some time, particularly for its application as a substrate in microelectronics [1]. Of late this material has found a variety of applications other than as an isolation region between devices, or the substrate of an active device. High resistivity SI GaAs is increasingly being used in charged particle detectors and photoconductive semiconductor switches (PCSS). PCSS made from these materials operating in both the linear and non-linear modes have applications such as firing sets, as drivers for lasers, and in high impedance, low current Q-switches or Pockels cells [2-4]. In the non-linear mode, it has also been used in a system to generate Ultra-Wideband (UWB) High Power Microwaves (HPM) [5]. The choice of GaAs over silicon offers the advantage that its material properties allow for fast, repetitive switching action [6]. Furthermore photoconductive switches have advantages over conventional switches such as improved jitter, better impedence matching, compact size, and in some cases, lower laser energy requirement for switching action.

The rise time of the PCSS is an important parameter that affects the maximum energy transferred to the load and it depends, in addition to other parameters, on the bias or the average field across the switch. High field operation has been an important goal in PCSS research. Due to surface flashover or premature material breakdown at higher voltages, most PCSS, especially those used in high power operation, need to operate well below the inherent breakdown voltage of the material. The "lifetime," or the total number of switching operations before breakdown, is another important switch parameter that needs to be considered for operation at high bias conditions. A lifetime of $\sim 10^4$ shots has been reported for PCSS's used in UWB-HPM generation [5], while it has exceeded 10^8 shots for electro-optic drivers [2]. Much effort is currently being channeled in the study

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related to improvements of these two parameters- high bias operation and lifetime improvement for switches used in pulsed power applications. The contact material and profiles are another important area of study.

Although these problems are being pursued through the incorporation of different contact materials and introducing doping near contacts [2,5], it is important that the switch properties and the conduction mechanism in these switches be well understood such that the basic nature of the problems can be properly addressed. In this paper we report on these two basic issues related to the device operation, i.e., mechanisms for increasing the hold-off characteristics through neutron irradiation, and the analysis of transport processes at varying field conditions in trap dominated SI GaAs in order to identify the breakdown mechanism during device operation. It is expected that this study would result in a better understanding of photoconductive switches, specifically those used in high power operation.

PCSS MATERIALS

Since the semiconductor resistivity varies inversely as the free carrier concentration, both intrinsic and compensated (with high density of trap levels near the mid-gap) semiconductors [7,8] having low free carrier concentrations are high resistivity materials. Charge transport in these two material types, however, differs. Compensated materials have better charge transport characteristics because their properties are very similar to "lifetime" semiconductors where the trap concentration defines the "screening length" (a parameter related to the Debye length) which is small compared to the diffusion length. Intrinsic materials are of the "relaxation" type, where the dielectric relaxation time is large and comparable to the minority carrier lifetime thus affecting the performance of the PCSS as a whole [9].

The compensated materials are made through various growth techniques such as liquid encapsulated Czechoraski (LEC), horizontal Bridgeman (HB), vertical gradient freeze (VGF) as well as other methods. It is possible that any two compensation techniques may give the same value for the material resistivity; however the various trap levels and impurity types in the materials may affect the conduction properties and the characteristics of the photoconductive switch [8]. Hence, in understanding device parameters such as rise time and switch lifetime, it is important to distinguish the material type, compensation processes, and the resistivity of the material. In this study we have targeted two device types of similar material, both LEC-grown SI GaAs. The switch geometry however is different. One of the devices has lateral (same side) forward-biased p and n-type contacts and operates in a comparatively lower DC field when operated in forward bias for increased device lifetime. The other has two n-type Rogowski profiled opposed contacts made from refractory materials and is also used in high power microwave generation. When reverse-biased, the lateral switch operates at similarly high DC fields as the opposed contact device, but with decreased contact longevity.

NEUTRON IRRADIATED PCSS

The effects of neutron irradiation on the properties of conductive GaAs have been extensively studied and reported effects include such phenomena as the degradation of free charge carrier mobility, removal of free charge carriers, and changes in the carrier lifetimes [10]. However, there is not much available data on SI GaAs since, until recently, these materials were used for device isolation and carrier transport was not a major concern. Capacitance-voltage analyses of undoped SI materials used in detectors have also shown an increase in the effective space charge concentration with fluence when they are subjected to neutron irradiation, thus implying the introduction of deep level defects [11]. The effect of neutron irradiation (fluence ~ 10^{17} n/cm^2) also results in an increase in the resistivity of the materials of the detectors [12].

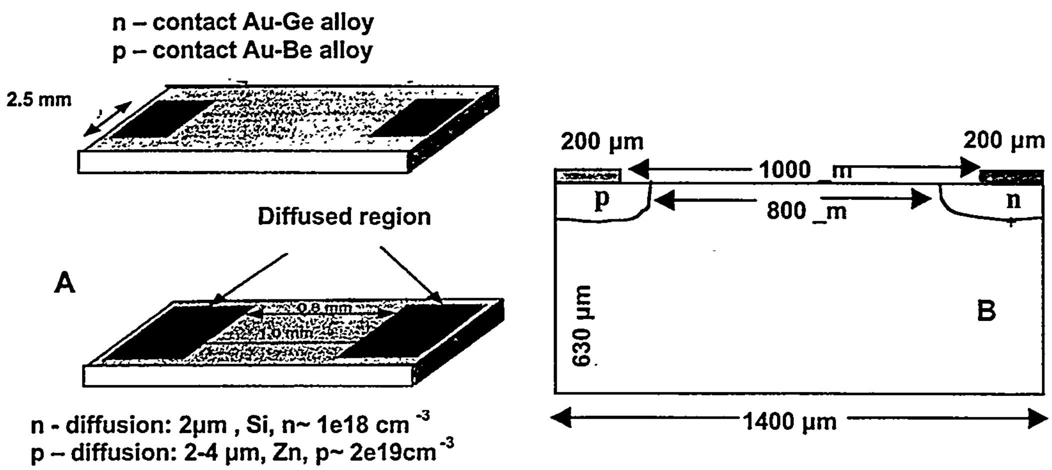

Figure 1. Photoconductive switches used in experiments [A] and simulation mesh [B]. The distance between the contacts and diffused layers was also maintained in the simulation mesh.

Since increased resistivity would facilitate higher bias operation and is expected to improve the rise time, experiments were conducted with the lateral devices at the Sandia Laboratories facilities. Two switch types (Figure 1A) were studied, one with p and n contacts to SI and the other with p^+/n^+ diffused layers below the contacts. Figures 2A and 2B show the I-V characteristic for the diffused contact devices before and after neutron irradiation. Hysteresis in the curves is evident, with the blue data show the ascending part of the voltage sweep and the black data showing the descending part.

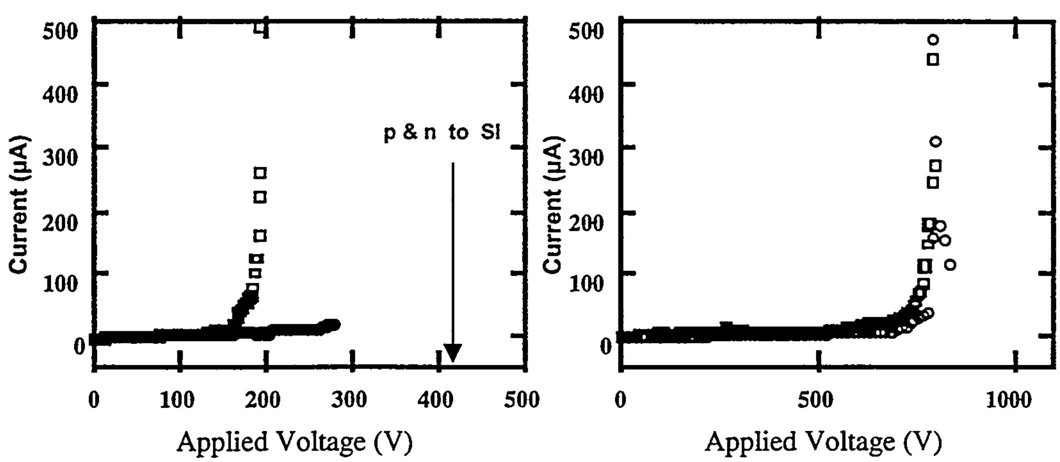

Figure 2. [A] Pre-neutron irradiation I-V for a 0.8 mm gap PCSS with diffused n/p layer below the contact. The response of the SI contact PCSS is indicated by the arrow line. [B] Post irradiation response of the diffused contact PCSS.

The device was exposed to a wide energy spectrum neutron flux with a maximum fluence of 10^{17} n/cm^2. The SI contact devices were not irradiated and its pre-irradiation I-V characteristic showed a steep increase at ~ 400 V, which is well beyond that of the diffused contact type (~ 260 V, Figure 2A). The effects of neutron irradiation results in an improved hold-off characteristic of the diffused contact device (2B).

The simulated response of the devices, obtained using the SILVACO [13] device simulation code is shown in Figure 3. This commercial code provides for a 2 and 3-D semiconductor device simulation and includes a large number of models and parameters to simulate physical conditions in devices. In addition, it also allows for user-defined model parameters as input through a C-interpreter. Figure 1B shows the 2-D device profile used in mesh generation. There are approximately 4000 grid points and simulation parameters including charge trapping and de-trapping at defect sites, carrier-carrier scattering, concentration and field dependent mobilities etc. The vendor supplied EL2 concentration of the wafer was ~ 10^{16} /cm^3 and its energy level was 0.730 eV. We have assumed that neutron irradiation induced EL2/EL6 traps have been generated [14], and hence the effective capture cross-section has increased. The dominance of the post-irradiated samples was shown through increasing the electrons capture cross section of the defect levels. Other simulation and model parameters were the same as in reference [14].

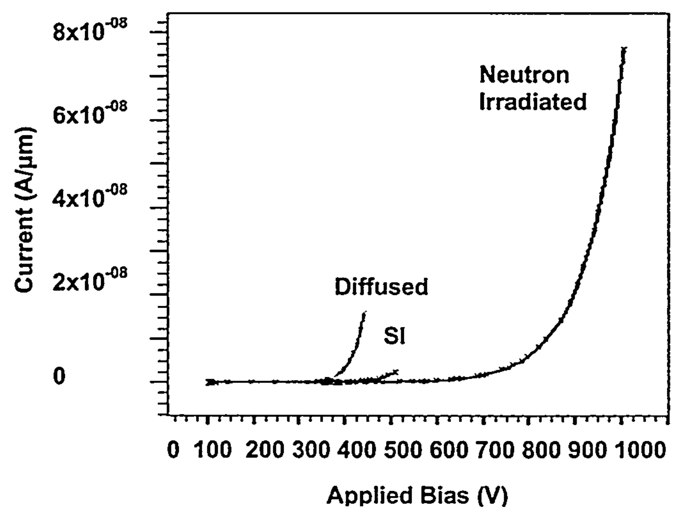

Figure 3: Simulated I-V for the three PCSS types.

Since the n^+/p^+ diffusion layer below the metals is conductive, the effective distance between the contacts for this PCSS is 0.8mm. For the SI contact PCSS the distance is 1.0 mm and the steep rise measured voltage is 400 V. Thus the voltage for steep rise for the diffused contact PCSS can be predicted by the relationship, $V_D = \frac{V_S . d_D^2}{d_S^2}$, where the subscripts D and S refer to the diffused and SI contacts [15]. Thus V_D ~ 256 which is very near the measured value as shown in Figure 2. Unstable filamentary characteristics [16], high field pockets and trap filled regions [17], however, are likely to be aggravated by neutron damage. Thus a post-irradiated analysis involving high power conduction in the on state of the switch may be required for these switches.

CARRIER TRANSPORT WITH VARYING BIAS

Simulations for the opposed contact PCSS show [Figure 4A] current controlled negative resistivity CCNR characteristic (S-shaped I-V). This characteristic is open circuit stable, i.e., if the device of area A is operating at voltage X and the current density is J_X, it achieves stability at point X_1 [see Figure 4B]. If the current at X_1 is J_1 and is carried by an area a, one can easily derive equation (2) [inset, 4B]. Since $J_1 >> J_2$, then $a << A$. Thus a very small area carries a large amount of current, which is a case for filamentation [17]. For switches that operate at high fields, the CCNR characteristic may be due to impact ionization. For lower fields where negative differential mobility is due to the transfer of electrons from a high-mobility energy valley to a low-mobility higher energy satellite valley the I-V characteristics is voltage controlled negative resistivity type (N-shaped). For such cases the device response is a traveling space-charge accumulation, rather than filamentation [15, 18]. However, filamentation has been observed in most of the lateral PCSS [2] operating at lower bias. The reason for this may be due to the regenerative effects of the double injection phenomena [17]. This increase due to double injection is shown in Figure 5. This regenerative effect brings about a sharp increase in current and the I-V characteristic is similar to the current controlled negative resistivity effect [Figure 4B].

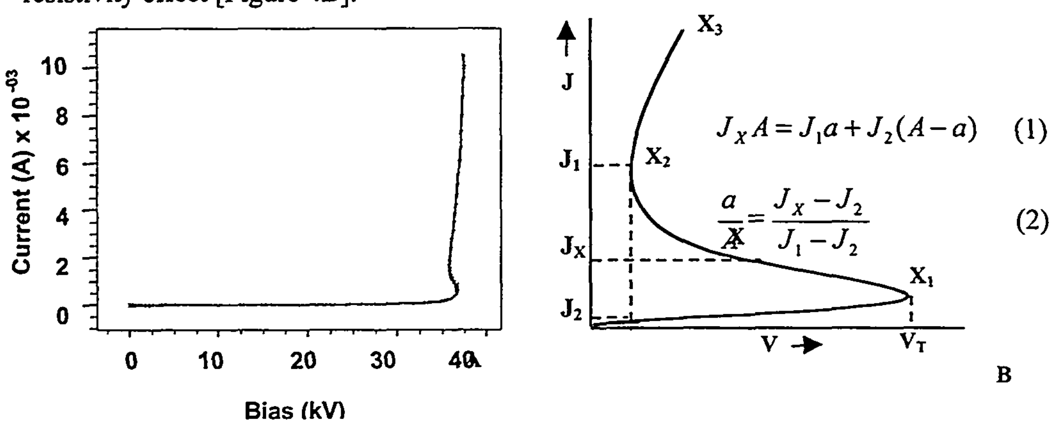

Figure 4. Simulated response at high bias showing negative resistivity [A] and conditions leading up to filamentation [B].

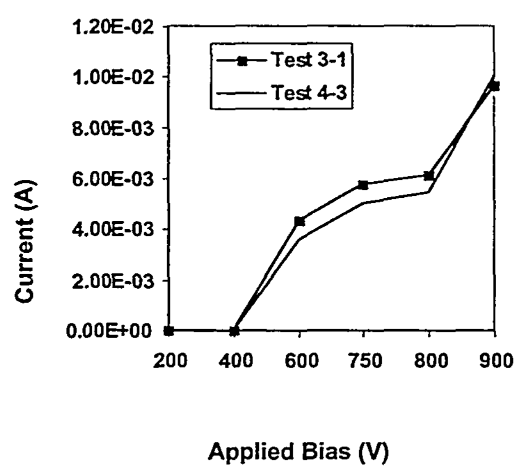

Figure 5. Low voltage I-V characteristics for a trap dominated PCSS showing an increase in current at 800 V.

The switch material, for which the I-V is plotted, has a resistivity of 1.0×10^{07} Ω-cm with EL2 traps near mid-gap. Measurements were performed using a HP-4142 Parametric Analyzer and the unit used for the measurement was a HP41423A, High Voltage Source/Monitor Unit (HVSMU) with a range from 2 mV to 1 kV and a supply current from 2 pA to 10 mA. The presence of electrons also lowers the space charge near the anode, and more holes are injected, increasing the current further.

CONCLUSION

We have presented experimental and simulation results for a SI GaAs PCSS with a high concentration of traps and discussed the results in terms of the dominance of the trap levels in determining the I-V characteristics of the devices. Experimental results and simulation analyses indicate that, when subjected to neutron irradiation, there is an improvement in the hold-off characteristics of the devices, which may lead to higher voltage operation and thus an improvement in the rise time of the device. The maximum energy transferred to the load would also increase, thereby improving the overall device characteristics. The filamentary conduction processes of the PCSS are more susceptible to failure if a large number of defect sites are formed in the device during a radiation transient. This is mainly because defects bring about inhomogenous conduction.

Acknowledgements

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REFERENCES

[1] C. Y. Chang and F. Kai, *GaAs High-Speed Devices, Physics, Technology and Circuit Applications*, John Wiley & Sons, Chapters 1 and 2, 1994.
[2] A. Mar, G. M. Loubriel, F. J. Zutavern, M. W. O'Malley, W. D. Helgeson, D. J. Brown, H. P. Hjalmarson and, A. G. Baca, "Doped Contacts For High-Longevity Optically Activated, High Gain GaAs Photoconductive Semiconductor Switches" IEEE Trans. Plasma Sci., Special Issue: Pulsed Power Science and Technology, to be published 2000.
[3] K. Zdansky, J. Santana, B. K. Jones and T. Sloan, "Modeling of Particle Detectors Based on Semi-insulating GaAs," Proceedings of the Third International Workshop on Gallium Arsenide and Related Compounds, Tuscany, Italy, Editors P. G. Pelfer, J. Ludwig, K. Runge and H. S. Rupprecht, World Scientific, New York, NY, 1995, p.78.
[4] G. M. Loubriel, F. Zutavern, A. G. Baca, T. A. Plut, W. D. Helgeson, M. W. O'Malley, M. H. Ruebush and D. J. Brown, "Photoconductive Semiconductor Switches," IEEE Trans. Plasma Sci., vol 25, p.124, 1997.
[5] J. S. H. Schoenberg, J. W. Burger, J. S. Tyo, M. D. Abdalla and M. C. Skipper and W. R. Buchwald, "Ultra-Wideband Source Using Gallium Arsenide Photoconductive Semiconductor Switches," IEEE Trans. Plasma Sci., Vol. 25, p.327, 1997.
[6] M. D. Pocha and W. W. Hofer, "High-Speed Switching in Photoconductors," *High-Power Optically Activated Solid State Switches*, Editors A. Rosen and F. J. Zutavern, Chapter 3, Artech House, Norwood, MA, 1994.
[7] R. B. Darling, "Electrostatic and Current Transport Properties of n^+/semi-insulating GaAs Junctions," J. Appl. Phys., vol. 74, p.4571, 1993.
[8] N.E. Islam, E. Schamiloglu, J.S.H. Schoenberg, and R.P. Joshi, "Compensation Mechanisms and The Response Of High Resistivity GaAs Photoconductive Switches During High Power Applications," submitted to IEEE Trans. Plasma Sci.

[9] E. Schamiloglu, N. E. Islam, C. B. Fledderman, B. Shipley, R. P. Joshi, and Z. Zheng, "Simulation, Modeling and Experimental Studies of High Gain Gallium Arsenide Photoconductive Switches for Ultra Wideband Applications", *Ultra Wideband Short Pulse Electromagnetics 4*, Edited by Hevman et. al., Kluwer/Academic Publishers, New York, NY, 1999, p 221.
[10] D. Pons and J. C. Bourgoin, "Irradiation Induced Defects in GaAs," J. Phys. C vol.18, 1985, p.3839.
[11] F. Dubecky, J. Betko, M. Morvic, J. Darmo, I. Besse, l. Hrubein, S. Halvac, M. Benovic, P. G. Pelfer, E. Gombia and R. Mosca, "Neutron Irradiated Undoped LEC SI GaAs: I. Galvanometic, I-V, PC and Alpha Detection Study," Gallium Arsenide and Related Compound, Editors P. G. Pelfer et. al., World Scientific, New York, NY, 1996, p152.
[12] F. Dubecky, F. Dubecky, T. Lalinsky, P. G. Pelfer, S. Halvac, E. Gombia, and R. Mosca, "Neutron Irradiated Undoped LEC SI GaAs: II. C-V and Deep State Analysis," Gallium Arsenide and Related Compound, Editors P. G. Pelfer et. al., World Scientific, New York, NY, 1996, p158,
[13] SILVACO International, ATLAS User's Manual, www.silvaco.com
[14] G. M. Martin, E. Esteve, P. Langlade and S. Markam-Ebeid, "Kinetics of Formation of the Midgap Donor EL2 in Neutron Irradiated GaAs Materials," J. Appl. Phys. Vol. 56, p.2655, 1984.
[15] J. J. Mares, J. Kristofik, V. Smid, and K. Jurek, "Impact Ionization and Space Charge Effects in SI-GaAs,"Semi-Insulating III-V Materials, p171, Edited by M. Godlewski, World Scientific, (1994).
[16] N. E. Islam, E. Schamiloglu, C. B. Fleddermann, J. S. H. Schoenberg, and R. P. Joshi, "Analysis of High Voltage Operation of Gallium Arsenide Photoconductive Switches Used in High Power Applications," J. Appl. Phys. vol. 86, p.1754 1999.
[17] S. K. Gandhi, *Semiconductor Power Devices,* Chapter 1 and 2, John Wiley & Sons, New York, NY, 1977.
[18] S. M. Sze, *Physics of Semiconductor Devices*, 2nd Edition, Chapter 11, John Wiley and Sons,New York, NY, 1981.